PROBLEMS IN THE MEASUREMENT OF LONGITUDINAL SAPWOOD PERMEABILITY AND HYDRAULIC CONDUCTIVITY

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ABSTRACT

Almost all published data on hydraulic conductivity (the longitudinal water-permeability of green sapwood) prior to 1963 are seriously in error because both water permeant and wood specimens were not deaerated. Faulty deaeration procedures affect most subsequent values. The resulting air embolism, already demonstrated for seasoned wood, is found here to affect green (**Pinus radiata**) sapwood also.

The end-surfaces of permeability specimens need to be cut cleanly to minimise extraneous surface resistance to gas- or liquid-flow.

For conifer wood (green or seasoned) there exists a minimum specimen length of about 20 mm below which longitudinal permeability values are greatly in excess of the bulk permeability. Furthermore, on air-seasoning, the fraction of bordered pits in the earlywood that aspirate is much smaller for a specimen shorter than 20 mm than for a longer specimen. The permeability of such a short specimen may thus be more than one hundred times the bulk permeability of the seasoned wood.

The gas-permeability of an air-dried wood specimen is affected additionally by the moisture content of the wood, the humidity of the gas, and the drying rate of the wood during seasoning. Because the drying schedule has to be specified, gas permeability values are of limited usefulness.

INTRODUCTION

Work on the permeability of wood, published over a long period, reveals a wide disparity in results and observations. This paper attempts to clarify some of these apparent inconsistencies, which on the whole are due to air-embolism in the flow channels of green wood, and changes in permeability that occur during drying.

Permeability is a measure of the ease of flow of a permeating fluid. It is determined by measuring the rate of flow of fluid through a wood specimen of known length and cross-sectional area while a known pressure difference is applied across it. It is calculated from the equation:

$$K = \frac{QL\eta}{A\Delta P} \qquad (1)$$

where K = permeability
Q = flow rate
L = length of the specimen
η = viscosity
A = cross-sectional area of flow
ΔP = pressure difference across the specimen

The S.I. unit of permeability is the m^2; if Q is measured in ml/s, L in cm, η in cP, A in cm^2 and ΔP in atmospheres the permeability unit is called the darcy (1 darcy = $9.87 \times 10^{-13} m^2$).

In the field of wood-permeability, the term hydraulic conductivity is used exclusively to refer to the longitudinal permeability of green (i.e., unseasoned) xylem. Some authors omit the viscosity term; this has been reviewed by Heine (1971).

Two types of fluid can be used; liquids and gases. These will be dealt with separately. In practice, water is the only liquid used for measuring permeability.

WATER PERMEABILITY OF WOOD

Wood permeability can be a meaningful concept only if during an experiment the rate of flow of water through wood can be maintained unchanged over a period of time. In the past many investigators observed a rapid decline of flow rate. Huber and Merz (1958) attributed this, for conifers, to pit aspiration caused by excessive pressure on the torus. However, the phenomenon also occurs for hardwoods (Narayanamurti *et al.*, 1951).

Kelso, Gertjejansen and Hossfeld (1963) showed than constant flow through wood (air-seasoned resaturated Sitka spruce) can be achieved provided the wood and the water are thoroughly degrassed before use. They attributed the decrease in flow rate with time to the formation of bubbles, from gases dissolved in the water, at reduced pressure areas where constrictions in the wood (e.g. pits) cause a very high local flow rate. The bubbles formed are carried downstream where they cause blockage. However, even in 1971 their explanation of the phenomenon was still treated with considerable caution by Zimmermann and Brown (1971; p. 197-8).

Kelso *et al.* (1963) used freshly distilled (and hence partially deaerated) water which they thoroughly filtered through a millipore filter to remove nuclei for gas bubble formation. They then passed the water through a filter consisting of tightly packed surgical cotton. The flow rate through the cotton interstices was so high that (by Bernoulli's principle) very large localised pressure reductions occurred, to well below atmospheric pressure. These caused air bubbles to form, which were then trapped further along the filter or just beyond, so that the water that finally flowed through the permeability specimens was practically deaerated. The function of the cotton filter has been misunderstood by several subsequent investigators who did not realise that its deaerating function does not depend on normal filtering action, but on cavitation caused by high interstitial flow rates. Thus, Lin, Lancaster and Krahmer (1973) obtained a permeability value for Western Hemlock only 2% of that obtained by Erickson and Crawford (1959) who did obtain constant flow. Lin *et al.* (1973), like Huber and Merz (1958), incorrectly attributed their time dependent flow rate in the sapwood to pit aspiration.

Megraw (1967) simplified Kelso's system by deaerating water under vacuum in an ultrasonic cleaning bath.

Permeability of Green Sapwood

Booker (1976) deaerated water by ultrasonic cavitation under vacuum. The ultrasonic generator used was a "Soniprobe" (Dawe Instruments Limited). The piezoelectric elements generate an intense pulsed 20 kHz sound wave which is concentrated by a tapered horn. The tip of this horn was in contact with the water to which the vacuum was applied, causing vigorous "frothing" for several minutes until deaeration was complete. This treatment decreased the oxygen content of aged double distilled water from 8.29 mg/litre to 0.453 mg/litre. Presumably the nitrogen content is reduced also by about 95%.

This, and untreated filtered distilled water, were then used in permeability experiments.

For a 20 mm long radiata pine specimen, degassed by evacuation under water, using ordinary filtered distilled water a rapid decrease in flow rate occurred. When deaerated filtered distilled water was used this did not occur (Fig. 1). These results show that air embolism is also the mechanism responsible for the time-dependent flow rate observed for the green sapwood of conifers, as was already proved by Kelso *et al.* (1963) for resaturated air-seasoned (Sitka spruce) heartwood.

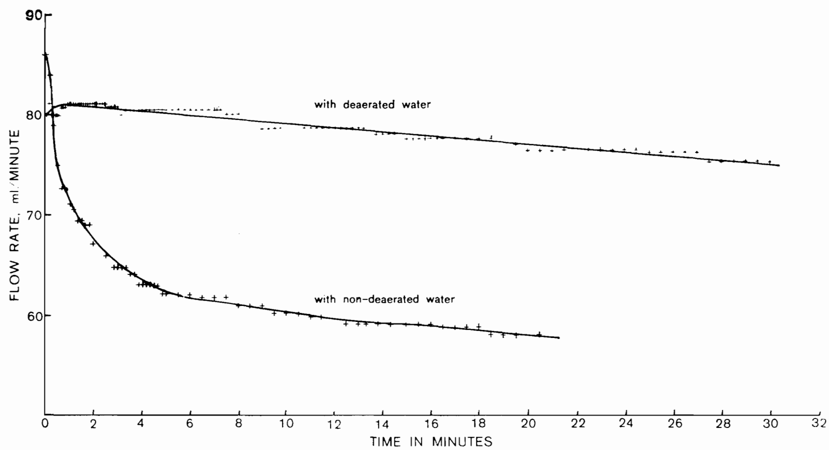

FIG. 1—Variation of flow rate with time for two radiata pine specimens of outer sapwood of a mature tree. The specimens were degassed but not end-matched. Distilled filtered (100 nm) water was used; with and without prior deaeration in upper and lower traces respectively.

Specimen length and surface preparation

The results in Fig. 1 are from 20-mm long specimens microtomed across the ends before use to expose an undamaged surface. The tracheids are cut across, thus exposing the full lumen area to water flow, i.e. eliminating the resistance due to surface damage from sawing. This increases the permeability dramatically; in one run the flow rate increased from 26.3 ml/min for a specimen with sawn ends to 35.6 ml/minute after microtoming, i.e., by 35%.

The specimen length of 20 mm was chosen because shorter specimens possess an abnormally high permeability (Fig. 2). Water can freely enter the lumens on each side of a microtomed specimen, thus reducing the effective permeation length by approximately one tracheid length in a total of about six. For specimens longer than 20 mm it becomes difficult to ensure that inflow and outflow are properly aligned with respect to the grain.

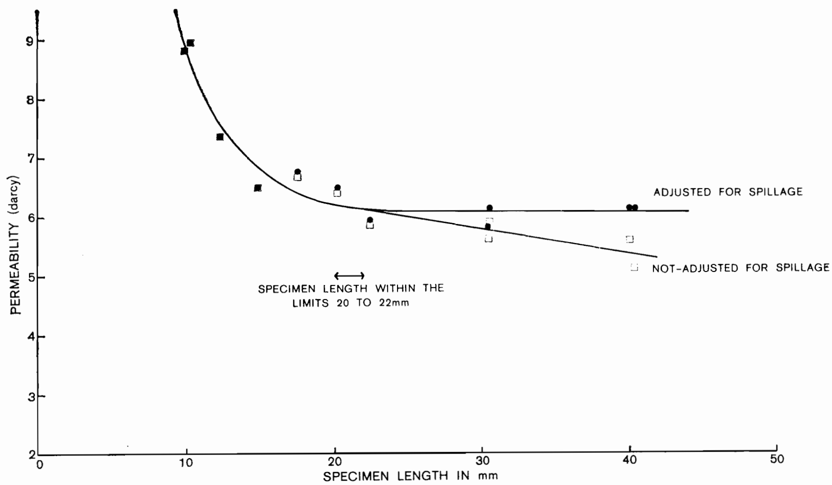

FIG. 2—Permeability as a function of specimen length.

Flow dynamics

Chen and Hossfeld (1964) passed deaerated aqueous glycerine solutions through resaturated air-seasoned Sitka spruce heartwood and showed that wood obeys Darcy's law (eqn. 1 above) with respect to viscosity.

Sucoff, Chen and Hossfeld (1965) have investigated the relationship between flow rate and pressure difference for the green xylem of *Thuja occidentalis* L. (Northern white cedar) at very high pressures and rates of flow. They found that when the pressure gradient exceeded 2.2×10^6 N/m^3 and the flow rate 5 litre/s/m^2 the relationship between flow rate and pressure drop becomes non-linear and obeys a quadratic equation. Permeability lost at high pressure differences is regained immediately and almost completely when the pressure difference is reduced. This rules out pit closure by non-elastic yielding of the margo strands as their recovery would be incomplete as well as time-dependent. The reproducibility of the results rules out air embolism, as does the fact that the permeability of about 3 darcy is very similar to that of the sapwood of other conifers. The explanation of Sucoff *et al.* for these results, namely turbulence and non-linear laminar flow, is almost certainly correct. Their most important result is, however, that flow rate and pressure drop are linearly related below 3.2 p.s.i./cm (2.2×10^6 N/m^3), so that when deaerated water is passed through green xylem at normal experimental pressures permeability is indeed a constant characteristic for the wood.

Because it was not known prior to 1963 that it is essential to deaerate both wood and water, almost all green sapwood permeability values in the pre-1963 literature are suspect and usually far too low (e.g., Dixon, 1907; Farmer, 1918). Even after 1963 the deaeration methods are often inadequate or absent (e.g., Peel, 1965; Heine, 1970); Lin *et al.,* 1973; Tesoro *et al.,* 1974). The most accurate longitudinal green sapwood permeability values that have been published for conifers are those by Erickson and Crawford (1959) and Comstock (1965), despite the fact that Comstock used specimens only 9 mm long.

The Effect of Tyloses on the Permeability of Hardwoods

In many hardwood species the vessels in the heartwood of the living trees are blocked off by tyloses, while the sapwood is completely free from them. If such a tree is injured or felled tyloses form in the sapwood near the affected area (Ermich, 1964; Schmidt, 1967). Tyloses can grow rapidly in the sapwood of some species; for instance, Murmanis (1975) reported that tyloses could already be observed in the sapwood of *Quercus rubra* after 2½ hours when the wood was collected during the active growth season and stored at room temperature.

Tyloses sharply reduce the permeability of the wood in which they form (Schmidt, 1967). To measure the permeability of the sapwood as it existed in the living tree before excision, it may be necessary to perform the surface preparation and deaeration of the specimens at low temperature (less than 15°C according to Murmanis (1975)). Also the permeability can be determined during the dormant season (Murmanis, 1975). Whether or not such steps are required depends on whether the species investigated forms tyloses, and their rate of growth.

In most hardwoods the vessels have a much larger diameter than the tracheids of conifers, and the perforation plates usually offer less resistance to flow than conifer pits. Consequently deaeration will be less essential for hardwoods than for conifers. However, the results of Narayanamurti *et al.* (1951) show that flow in hardwoods can also be affected by air-embolism, and hence it is still advisable to completely deaerate the water permeant before use.

Comparison of the Earlywood and Latewood Permeability in Sapwood

There is considerable confusion in the literature as to whether in conifers the earlywood or the latewood in the sapwood is more permeable (Comstock, 1965; Fogg, 1969; Bramhall and Wilson, 1971). The main reason for this is the very large changes in permeability that occur due to pit aspiration when wood is seasoned. The second cause of confusion arises from the use of Acid Fuchsin dye. Harris (1961) has shown that Acid Fuchsin dye diffuses rapidly from the earlywood into the latewood of green conifer wood. Hence this dye should never be used to identify water pathways in green conifer wood; instead a non-diffusing dye such as Toluidine Blue or Safranin should be used.

Harris (1961) and the author (unpubl.) have shown with dye experiments that in green sapwood the latewood permeability is negligible compared to that of the earlywood for most species. [*Pinus radiata, P. contorta, P. nigra, Pseudotsuga menziesii, Populus* spp., *Nothofagus* sp.]. In most conifers the position is completely reversed for air-dried sapwood. When green sapwood is air-dried, nearly all pits in the earlywood aspirate. Phillips (1933) found that pit closure occurs gradually with loss of moisture down to the fibre saturation point, and that at this point nearly all of the earlywood pits become aspirated, while a certain portion of the latewood pits do not become aspirated. As a result after air drying the permeability of the latewood in the sapwood exceeds that of the earlywood but the permeability of both is sharply reduced. Erickson and Crawford (1959) found that the permeability of Douglas fir and Western hemlock sapwood was reduced after air-drying to 1 to 3% of the value for green wood. They demonstrated that latewood is more permeable than earlywood after air seasoning by passing dye solution through the resaturated wood. They also showed that the wood permeability is critically affected by the rate of air drying; the flow through their slowly seasoned specimens averaged about 50% higher than that for their medium- and fast-dried specimens.

Kininmonth (1970, p.87) has established that the degree of pit aspiration depends upon specimen length (Table 1). As the specimen length increased the reduction in permeability caused by drying and resaturation increased from 40-60% for 7.2-mm specimens to 100-200 fold for 25.7-mm specimens. It appears that, when a relatively short specimen is dried from both ends, the bordered pits do not aspirate completely. There seems to be a critical length of about 20 mm beyond which the permeability becomes constant.

TABLE 1—Effect of specimen length on the longitudinal permeability of **P. radiata**

Specimen	Length (mm)	Flow rate (ml/min) at 10 cm Hg pressure drop: green (water)	dry (air flow)	resaturated (water)	Ratio of re-saturated to green flow rates %
1A	7.2	80.0	2000+	45.0	56.3
1B	13.1	40.0	1200	12.5	31.3
1C	18.7	34.8	96	0.4	1.1
1D	25.7	22.8	60	0.2	0.9
1E	36.8	18.0	26	0.1	0.6
2A	7.2	54.0	2000	24.6	45.6
2B	13.0	27.4	260	1.0	3.6
2C	18.8	24.0	73	0.44	1.8
2D	25.7	18.8	53	0.08	0.45
2E	36.7	12.4	24	0.06	0.48

The author partially confirmed Kininmonth's results by passing dye solution through resaturated seasoned 13-mm and 25-mm radiata pine specimens. For the 13-mm specimens dye flowed very rapidly through the earlywood, while for specimens of 25 mm or longer the dye flowed very slowly through the latewood and a few resin canals. Hence the degree of pit aspiration in the earlywood is strongly dependent upon specimen length up to a length of about 20 mm. Because of this dependence of the permeability of air-dried wood upon both specimen length and rate of drying, many of the gas-permeability results in the literature are of doubtful value.

Erickson and Crawford (1959) have shown that the permeability of green conifer sapwood can be retained almost completely on air-drying if the water in the wood is first exchanged with organic solvents to avoid pit aspiration. Unfortunately the permeability is then seldom identical to that of the green sapwood. Sachs and Kinney (1974) claim that practically all solvent exchange methods damage the pit margos by enlarging the pores. This would increase the permeability, presumably balanced by a limited amount of pit aspiration on drying. An additional complication is that solvent exchange may remove extractives from the wood and open resin canals, resulting in a permeability higher than that of the green wood.

Hardwoods do not possess bordered pits, but have perforation plates between vessel segments. Nevertheless the permeability of hardwoods is also markedly affected by air-drying (Choong, Tesoro and Manwiller, 1974; Chen, 1975).

THE GAS PERMEABILITY OF WOOD

At first sight it would seem to be much simpler to measure the gas-permeability of wood than its water-permeability, as this completely avoids the problem of air-embolism encountered when water is used. Unfortunately this is not the case, as there are many problems in regard to techniques as well as the interpretation of results.

Choong, McMillan and Tesoro (1975) have shown that surface preparation has a profound effect on the rate of axial gas flow through wood, and that the surfaces need to be microtomed or scalpel cut. This step was omitted by nearly all investigators.

A minimum specimen length of 20 mm will be required for two reasons. Firstly, for air-dried specimens less than 20 mm long the degree of pit aspiration depends on the specimen length. Secondly, it is probable that even for solvent-dried specimens a minimum length of 20 mm will be required for the same reasons as for the water-permeability specimens (cf. Fig. 2). This is contradicted by Buro and Buro (1959) who claim that air-permeability is independent of length for Scots pine (Kieferholz) from 7 to 35 mm. However, they polished the end faces of their specimens with emery paper, and the additional surface resistance so introduced would be a greater percentage of the total for the shorter specimens, thus counteracting the increased permeability of the shorter specimens.

Fogg (1969) discovered that it was impossible to achieve a constant flow rate with time when dry air was used as the permeant. He found that it was necessary to humidify the gas so that its moisture was in equilibrium with the moisture content of the wood, and that the permeability depends on the m.c. He also established that if during a drying cycle the m.c. is decreased below 6% irreversible changes occur in the wood, so that during each drying cycle the permeability increases further. Hence air-dried permeability specimens should never be oven-dried below 6% m.c.

Longitudinal gas permeability is generally investigated for one of the following reasons:

(1) To determine the ease of impregnation after the wood has been seasoned (of little importance in the field of timber preservation, as most preservative impregnation of conifer wood occurs in the transverse direction);
(2) to determine the effect of different seasoning treatments on permeability;
(3) to investigate the permeability properties of green wood as it occurs in the tree.

To investigate the ease of wood impregnation after drying the specimens must be dried according to the same schedule as the normal commercial drying method. Only this ensures the correct rate of drying, which in turn affects the degree of pit aspiration in the sapwood-earlywood.

Equivalence of Gas- and Liquid-permeability

The relationship of liquid-permeability and gas-permeability can be established by first determining the gas permeability, followed by saturation of the wood with the liquid permeant, after which the liquid permeability is measured (Comstock, 1967). For equivalence to exist the liquid may not cause swelling of the wood. To obtain gas-permeability values for conifers, comparable to the bulk water permeability values of green xylem, however, the specimens must be prepared as follows:

(1) The specimens must be microtomed (Choong *et al.,* 1975).
(2) The specimen length should be 20 mm or longer.
(3) The specimens must have been solvent exchanged very slowly (Sachs and Kinney, 1974) before being dried very gently. The solvent used may not remove extractives from the wood.
(4) The permeability must be extrapolated to infinite pressure (Comstock, 1967).

Finally, after the gas permeability has been measured the flow paths must be identified as solvent exchange and drying can open resin canals to flow that were closed in the green wood. The fraction of the permeation area occupied by earlywood should be measured, as the permeability of earlywood is much greater than that of latewood for solvent-exchanged wood.

For hardwood specimens similar techniques have to be used, and the development of tyloses has to be prevented.

Variation of Axial Gas Permeability with Position in the Tree

The axial gas permeability of air-dried (non-solvent-treated) wood has been related to height and cross-sectional position in the tree by several investigators: Krahmer and Côté (1963), Fogg (1969), Isaacs *et al.* (1971), Choong and Fogg (1972), and Choong, Tesoro and Manwiller (1974). Apart from work on air-seasoned wood, Beall and Wang (1974) solvent-exchanged Eastern hemlock sapwood, without microtoming their specimens. They found no significant relationship between longitudinal dry nitrogen-permeability and oven-dry density or tree height (20 m). In contrast, Comstock (1965) found a very significant increase in water-permeability with height for green wood of the same species. A similar correlation exists for green *Pinus radiata* (Booker and Kinninmonth, 1978) and *Populus deltoides* (Edwards and Booker, to be publ.). Results for air-dried wood have little relevance to permeability relationships in the living tree.

Even though the variation of green xylem permeability with height and/or cross-sectional position has never been adequately investigated by gas-permeability methods, further work in this area is clearly unwarranted because of limited practical application and relevance to the living tree, and because the problems of obtaining meaningful water permeabilities have been overcome.

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